

A new method of creating high intensity neutron source

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ABSTRACT

We propose a new scheme of producing intense neutron beam whose yields exceed those of existing facilities by many orders of magnitude. This scheme uses the recently proposed photon beam extracted from circulating quantum ions, which is directed to a deuteron target for photo-disintegration. The calculated neutron energy spectrum is nearly flat down to neV range, except a threshold rise and its adjacent wide structure. Hence, there exists a possibility of directly using sub-eV neutrons without a moderator. We shall have brief comments on promising particle physics applications using this large yield of neutron.

Keywords Neutron source, Heavy ion synchrotron, Quantum coherence, Gamma ray beam, Photo-disintegration of deuteron, Time-reversal invariance, Ultra cold neutrons

1 Introduction

Neutron is a powerful source to explore fundamental physics and is an indispensable tool in applications to material and life sciences. Despite of existing strong neutron sources using reactor and spallation facilities [1] new ideas of more intense sources [2] are obviously welcome from this point.

We propose in the present work a new scheme of accelerator-based neutron source. In addition to a potentiality of producing neutron yield much stronger than existing sources, this scheme creates a neutron spectrum calculable from the first principles and it is possible to use this source without using moderator [3]. The radiation safety and the heat generation problems appear less severe compared with existing methods.

For definiteness we consider an example to use the parameter of an existing accelerator, the SuperKEKB ring [4]. Hence we take a circumference of the ring ~ 3 km, and an ion boost factor in the range of $100 \sim 300$.

Our proposed idea of neutron source is depicted schematically in Fig(1). It consists of an ion synchrotron that produces an intense and well-collimated gamma ray beam based on [5], [6], a target area that produces neutrons by photo-disintegration of deuteron and a moderator system that transports neutrons to experimental sites. The option of direct slow neutron extraction without the use of moderator is possible.

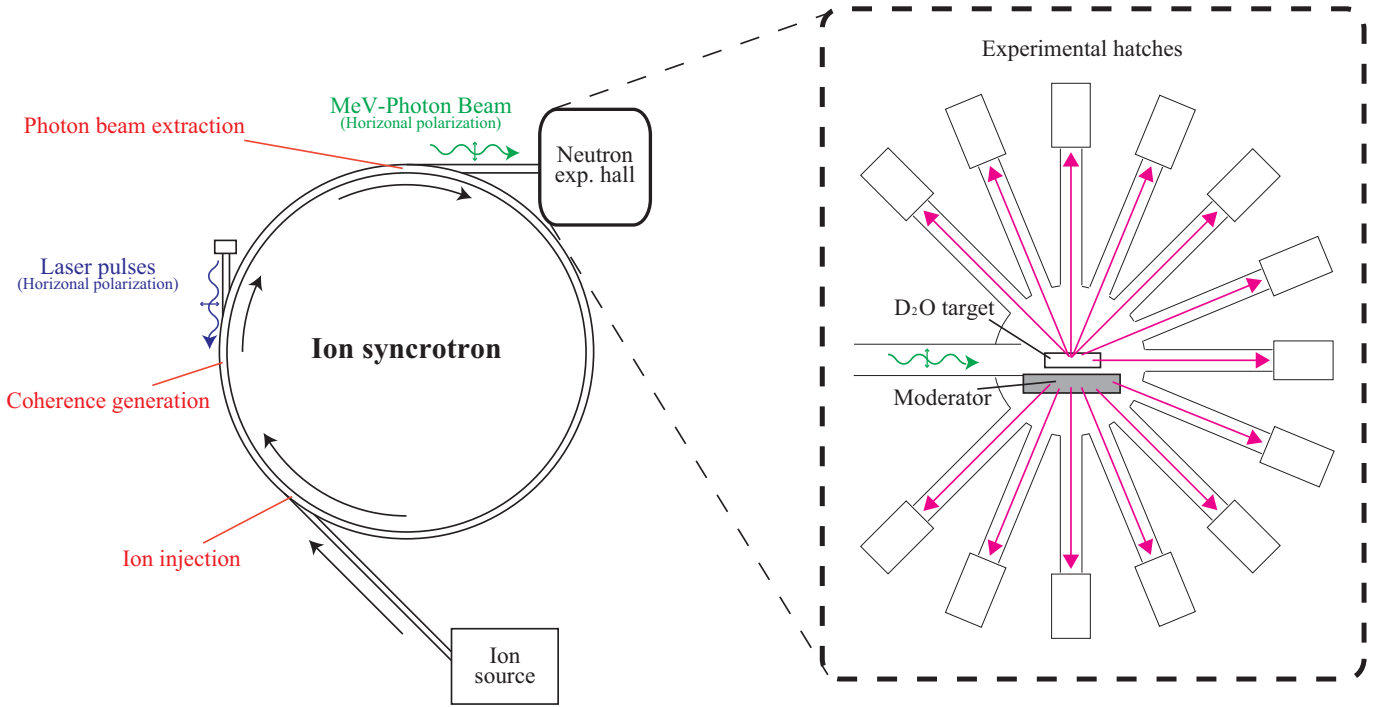


Figure 1: Schematic view of high intensity neutron beam facilities.

In the rest of this work we first discuss essential features of the photon beam from circulating ions at the synchrotron, and proceed to calculation of the neutron yield at the target. A brief discussion of particle physics applications that may become promising with high intensity neutron yield is added.

Throughout this work we use the natural unit of $\hbar = c = 1$.

2 Photon beam from quantum ion in circulation

It was recently proposed [5], [6] that quantum ions in circulation emit strong photon beam. The beam intensity depends on the coherence ρ_{eg} of quantum ions, which is defined for a state of quantum mixture,

$$|c(t)\rangle = \cos \theta_c |g\rangle + \sin \theta_c e^{-i\epsilon_{eg}t/\gamma} |e\rangle, \quad \rho_{eg} = \cos \theta_c \sin \theta_c. \quad (1)$$

The coherence given by ρ_{eg} is generated by irradiation of lasers from counter-propagating directions. In ordinary synchrotron radiation $\rho_{eg} = 0$ and the gamma ray emission discussed here is different from the synchrotron radiation. We use linearly polarized lasers in the ion orbit plane to select the dominant direction of neutron flux within the plane. Ion candidate state $|e\rangle$ (the ground state for $|g\rangle$) we consider here are He-like 2^3S state [7], [8], but there may be many other possibilities.

The emitted photons are limited by the solid angle area π/γ^2 near the forward direction to the circulating ion. The forward rate is given by

$$\left(\frac{d^2\Gamma_\gamma}{dx d\Omega}\right)_0 = \frac{A_{eg}}{4\sqrt{\pi}} N_I \rho_{eg}^2(t) \sqrt{\rho_{eg}} \frac{\gamma}{\sqrt{\beta}} \frac{1}{x} \left(\beta^2 x^2 - (x - \frac{1}{\gamma})^2\right)^{-1/4}, \quad (2)$$

using the dimensionless energy $x = \omega/\epsilon_{eg}$. The quantities introduced here are ρ the radius of the ring, N_I the number of ions in the ring, $\gamma = 1/\sqrt{1 - \beta^2}$ the boost factor, and A_{eg} the A-coefficient (decay rate) for $|e\rangle \rightarrow |g\rangle + \gamma$ of the level spacing ϵ_{eg} . Photon beam intensities, as illustrated in Fig(2) taking into account the de-coherence discussed below, are much stronger than any presently available photon beams.

It is important to estimate the coherence loss [9] in order to determine where in the ring the extraction of the photon beam is made. The basic equation of the time dependence and its solutions for the coherence loss is

$$\frac{d\rho_{eg}}{dt} = -\frac{G}{2}\rho_{eg}^3, \quad \rho_{eg}(t) = \frac{\rho_{eg}(0)}{\sqrt{1 + G\rho_{eg}^2(0)t}}, \quad \rho_{eg}(0) = \frac{1}{2} \sin(2\theta_c), \quad (3)$$

$$G = \frac{A_{eg}}{4\sqrt{\pi}} \sqrt{\rho_{eg}} \frac{\pi}{\gamma\sqrt{\beta}} \int dx \frac{1}{x} (\beta^2 x^2 - (x - \frac{1}{\gamma})^2)^{-1/4}, \quad (4)$$

where G was calculated by integrating the photon number over all emitted photon energies and angular area π/γ^2 . It is interesting to note that the asymptotic value in $t \gg 1/(G\rho_{eg}^2(0))$ is independent of the initial coherence $\rho_{eg}(0)$, $\rho_{eg}(t) \rightarrow 1/\sqrt{Gt}$.

We choose in the rest of calculation a parameter $\rho_{eg}(0)$ to be $1/10^3$, which is controllable by laser irradiation, and f to be around $1/4$ corresponding to the extraction point at $3/4$ km of the SuperKEKB ring. We assume throughout the present work that the circulation velocity β is constant despite of an ion energy loss caused by photon emission. It is implicitly assumed here that the ion energy is compensated by its acceleration, thereby justifying the assumption of the constant velocity approximation. We take in the present work He-like ions using “forbidden” $2^3S \rightarrow 1S$. Transitions of this type actually occur for high atomic number Z , their decay rates scaling with Z^{10} [8]. Using theoretical data of [7], we numerically fit the A-coefficient of He-like transitions, and use the level spacing derived from the relativistic Dirac equation. In presented figures of this work we took as an illustration He-like ions of Ca^{18+} , Zn^{28+} , Zr^{38+} .

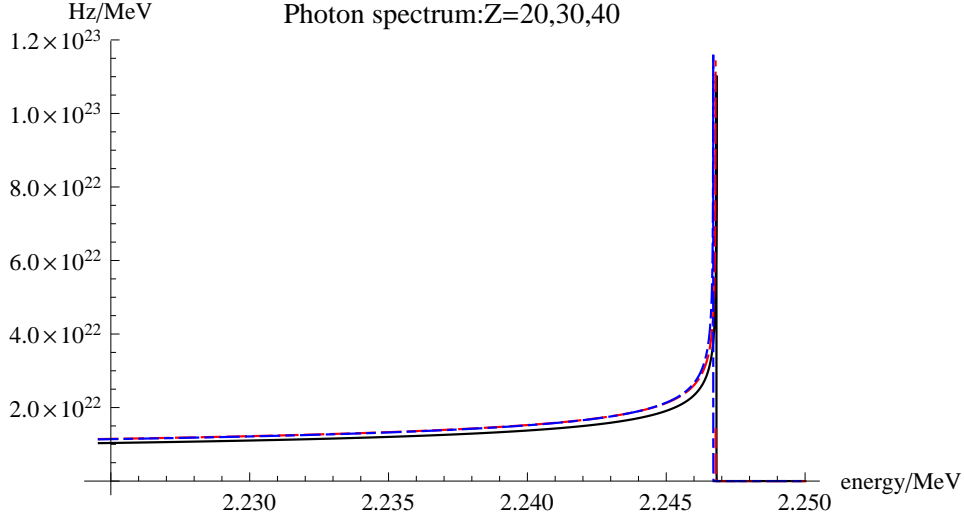


Figure 2: Photon spectrum above the photo-disintegration threshold, photons being emitted in the forward direction after extraction at ion turn of angle $\pi/2$ after laser irradiation. He-like ions of atomic number Z and the boost factor γ taken are $Z(\gamma) = 20$ (274) in solid black, 30 (121) in dashed red, and 40 (67.5) in dash-dotted blue. The boost factor γ here is taken to satisfy the condition $\omega_m \sim 2\gamma\epsilon_{eg}$ equal to the photo-disintegration threshold $S_n \times (1 + 0.01)$ (1 % away from the disintegration threshold). Relaxation width 1 eV, the number of ions $N_I = 10^9$, the initial coherence $\rho_{eg}(0) = 1/10^3$ (corresponding to the effective available ion number $N_I \rho_{eg}^2(0) = 10^3$) are assumed.

We include a relaxation width effect by multiplying the photon energy spectrum at ω_0 by a convolution factor $\Delta/((\omega_0 - \omega)^2 + \Delta^2/4)$ to be integrated over ω_0 . The relaxation width Δ is related to photon emission via $G\rho_{eg}^2(t)$, but other effects can give much larger width factor. Since results are insensitive to the actual value, we assume $\Delta = 1\text{eV}$ in our numerical computations. A resultant photon spectrum is illustrated in Fig(2).

3 Calculation of neutron yield

Emitted photon beam is directed to the target area where photo-disintegration occurs to produce neutrons. We place the target not too far from the extraction point of photon beam in order to be fully covered by the angle area within π/γ^2 . Deuteron photo-disintegration, $\gamma + D \rightarrow n + p$, have been analyzed both experimentally [10] and theoretically [11], [12] in great detail. They show that electric dipole (E1) contribution giving the angular distribution $\sin^2 \theta_n (1 + \cos(2\varphi_n))$ (θ_n is the neutron emission angle from the beam direction, while φ_n the angle out of the orbit plane) is dominant away from the threshold $\sim 2.2\text{ MeV}$, while the isotropic magnetic dipole (M1) contribution is important near the threshold. The differential photo-disintegration cross section we use (the photon energy ω given in MeV unit) is

$$\frac{d^2\sigma_{\gamma D}}{d\omega d\Omega} = \left(\frac{d\sigma_{\gamma D}}{d\Omega}\right)_0 \delta(\omega + m_D - K_n - \sqrt{m_p^2 + \omega^2 + p_n^2 - 2\omega p_n \cos \theta_n}), \quad (5)$$

$$\left(\frac{d\sigma_{\gamma D}}{d\Omega}\right)_0 = \left(62.77 \frac{(\omega - S_n)^{3/2}}{\omega^3} \frac{3}{8\pi} \sin^2 \theta_n + 0.692 \frac{\sqrt{\omega - S_n}}{\omega(\omega - 2.15)} \frac{1}{4\pi}\right) \times 10^{-27} \text{ cm}^2, \quad (6)$$

taking a numerical fit that includes both E1 and M1 contributions. The deuteron binding energy is denoted by S_n which is 2.22457 MeV [13]. The neutron kinetic energy $K_n = p_n^2/2m_n$ is related to the emission angle θ_n due to the two-to-two body reaction.

Using the cross section of photo-disintegration given as a function of $(\omega, \cos \theta_n)$, the neutron rate emitted at an angle θ_n measured in the ion orbit plane from the photon beam is given by

$$\left(\frac{d^2\Gamma}{dK_n d\cos \theta_n}\right)_{\varphi_n=0} = n_D L \sqrt{\frac{2K_n}{m_N}} \left(\left(\frac{d\sigma_{\gamma D}}{d\Omega}\right)_0 \Delta\Omega \left(\frac{d\Gamma_\gamma}{dx}\right)_0\right)_{\omega=X(K_n, \cos \theta_n)}, \quad (7)$$

$$X(K_n, \cos \theta_n) = \frac{1}{2} \frac{S_n(2m_N - S_n) + 2m_D K_n}{m_N - S_n - K_n + \sqrt{2m_N K_n} \cos \theta_n}. \quad (8)$$

The kinematic relation, $\omega = X(K_n, \cos \theta_n)$, among the photon energy ω , the deuteron emission angle θ_n and its kinetic energy K_n , proper to the two-body process was used. The quantity $n_D L$ is the deuteron number density per target cross area.

An advantage of the proposed scheme is that one can optimize the photon beam by a choice of accelerator parameters, Z and γ . Choose the maximum photon energy $\omega_m \sim 2\gamma\epsilon_{eg}$ to be near the threshold like $S_n < \omega_m \leq S_n(1 + \epsilon)$. For He-like ions this reads roughly as

$$\frac{S_n}{20\text{ eV}} < \gamma Z^2 \leq \frac{S_n}{20\text{ eV}} (1 + \epsilon). \quad (9)$$

Note that the required boost factor γ is at least larger than $S_n/(Z^2 20 \text{ eV}) \sim 10^3(10/Z)^2$. There exists a kinematic restriction: $\epsilon \geq S_n(1 - \cos^2 \theta_n)/(2m_N)$.

For numerical calculations we assume a liquid D₂O target of small cross sectional area of order 1 cm² transverse to the photon beam. In this type of targets one may ignore neutron scattering within the target D₂O. Furthermore, the effect of Compton scattering of the beam photon off atomic electrons can be taken into account by a simple beam reduction factor, $e^{-\mu z}$, with μ the attenuation coefficient [14] (dominated by the Compton scattering, hence $\mu \sim \sigma_C n_e$) and z the target location from the beam entrance. We assume for the target 1 cm² \times 20 cm D₂O to use the beam reduction factor of $\int_0^\infty dz e^{-\mu z} \sim 20 \text{ cm}$ (giving the total deuteron number $\sim 1.2 \times 10^{24}$). The circulating ion number is taken as $N_I = 10^9$ ($1/10^4$ of the number taken from that achieved for accelerated protons in TeV region), and the initial coherence as $\rho_{eg}(0) = 1/10^3$. With increased N_I the event rate linearly increases. The neutron yield given in the figures refers to the value per unit solid angle area at the given neutron emission angle.

The global feature of the neutron yield is shown in Fig(3), which shows yields much larger than those of exiting facilities: the yield numbers integrated over the entire neutron energy are to be compared with the designed J-PARC MLF value, which is of order, $10^{17}/4\pi \text{ Hz}$, at the target point. Neutron yields extracted at different angles have different maximum energy cutoffs, as shown in Fig(4). The total 100 neV range of neutron yield using the parameter set in the figures is $O(10^{10}) \text{ Hz}/100 \text{ neV}$ for $Z = O(30)$, as evident in Fig(5). This number is $O(10^{14}) \text{ Hz}/\text{meV}$ in the meV range. These large yields should be a great benefit to fundamental physics and other applications. The conventional use of moderators reduces the flux at target by an order of 10^3 , while this scheme gives a nearly flat spectrum down to neV range.

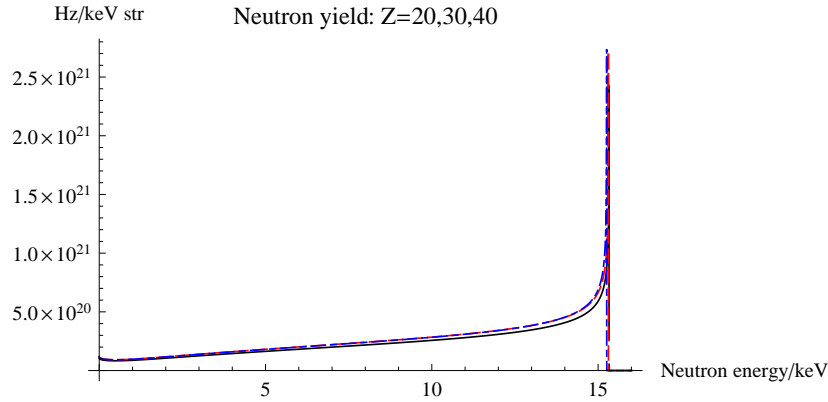


Figure 3: Neutron yield at an emission angle $\pi/6$ from the photon beam. The same set of (Z, γ) combination as in Fig(2) is taken. Relaxation width 1 eV, the number of ions $N_I = 10^9$, the initial coherence $\rho_{eg}(0) = 1/10^3$. the deuteron number $n_D L = 1.3 \times 10^{24} \text{ cm}^{-2}$ (roughly corresponding to 20 g per 20 cm target length) are assumed.

The large and flat yield shown here opens a new possibility of using directly the sub-eV neutron without a moderator. The example of Fig(5) uses the boost factor fine tuned to $S_n(1+0.01)/20 \text{ eV}$. A great advantage of our new scheme is that one can adjust the parameter ϵ of eq.(9) to precisely select the neutron energy

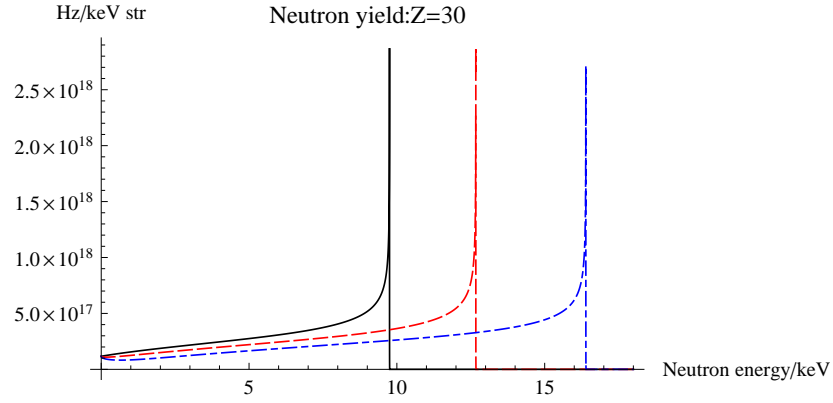


Figure 4: Neutron yields extracted at various angles: $\pi/2$ in solid black, $\pi/3$ in dashed red, and 0 (forward direction) in dash-dotted blue. Other parameters are taken the same as in Fig(3).

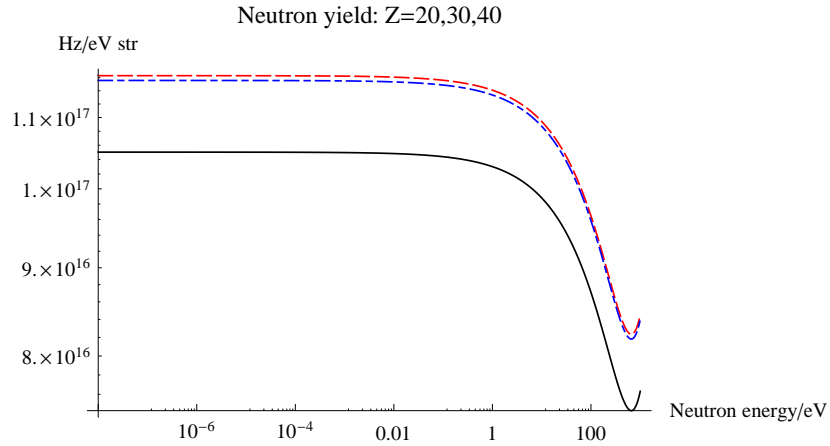


Figure 5: Neutron yield including the sub-eV range at angle $1/10^3$. Parameters are the same as in Fig(3).

region both from above and below, since the maximum photon energy $\sim 2\gamma\epsilon_{eg}$ is fixed by acceleration of ions and the minimum usable photon energy $\sim 2.2\text{ MeV}$ is determined from the threshold of deuteron photo-disintegration.

4 Summary and prospects

We proposed a method of how the intense photon beam produced from circulating quantum ions can provide high intensity neutron yields much stronger than those of existing facilities. The neutron flux thus obtained is pulsed in correlation with the bunch structure of circulating ions and timing of laser irradiation. Its calculated spectrum is nearly flat down to the neV range.

The success of high intensity neutron source project rests with R and D works on the photon beam in which it is important to realize a large value of parameter combination $N_I\rho_{eg}^2(0)$. We have assumed in our sample calculations that the total available ion number N_I is 10^9 , taking a value, $1/10^4$ of the achieved value from accelerated protons in the TeV region, and the initial coherence $\rho_{eg}(0) = 1/10^3$ which is controllable by laser irradiation. These values may or may not be optimistic for assumed ions, since one has to accelerate He-like ions in the intermediate Z range. If this choice of parameter set is too optimistic, one may attempt to move the position of extraction point closer to the laser irradiation point in order to obtain a higher gamma ray intensity. There may be other choices different from He-like ions. We have also studied the simple system of H-like E1 allowed $2^1P_1 \rightarrow 1^1S_0$ transitions. This system gives ~ 0.3 reduction of rates around $Z = 30$ in comparison with He-like system studied above. For more complicated system of ions a systematic atomic physics calculation is required to derive basic data of A-coefficients and level spacings. The systematic study of the optimal choice of the ion atomic number and the boost factor is clearly important for further development. As a target of photo-disintegration we considered deuteron in the present work. Another possibility worth of investigation is solid ^9Be target.

The rest of downstream facilities such as the target and the moderator is straightforward. Conventional moderator systems are useful for experiments employing thermal neutrons. If one wants to directly use sub-eV neutrons which are abundant at the deuteron target in the neutron source of our scheme, one may need construction of a reliable system of energy separation or a velocity selector.

With realization of high intensity neutron source, both fundamental physics and applications to material and life sciences may have brighter future. In particle physics one may list interesting applications with some comments. 1. UCN (Ultra Cold Neutrons). One stores neutrons below $\sim 300\text{ neV}$ in totally reflecting bottles, for instance in search for electric dipole moment (EDM) of neutron whose presence indicates violation of the fundamental symmetry, time-reversal symmetry. Our integrated rates are of order $10^{10}\text{ Hz}/(\text{str } 100\text{ neV})$. This may give a large storage integrated over a fraction of neutron lifetime. 2. T-odd triple product among the beta decay products of neutrons. A precise selection of the parent neutron momentum \vec{p}_n should help to search for a few types of T-odd observables, its presence indicating violation of time-reversal invariance. Precision experiments should be possible with a large neutron flux $O(10^{14})\text{ Hz}/(\text{str meV})$. Discovery of a finite triple product of this combination may indicate new physics beyond the standard electroweak theory,

since there is a wide gap between the present upper limit and expectation of the standard theory. We refer to references [15] on other applications. In a long run one is tempted to use this intense neutron source for resolution of the nuclear waste problem by nuclear transmutation.

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